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HUMAN OPERATOR PERFORMANCE OF
REMOTELY CONTROLLED TASKS:

A Summary of Teleoperator Research
Conducted at NASA's George C. Marshall Space Flight Center
Between 1971 and 1981

EXECUTIVE SUMMARY

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FOREWORD

This Executive Summary of Human Operator Performance of Remotely Controlled Tasks, Essex Report H-82-01, is intended to briefly describe the Marshall Space Flight Center (MSFC) teleoperator research laboratories and outline significant research findings and design criteria which should be considered in the development of teleoperator systems for space applications. The supporting documentation for this summary is detailed in the reference and bibliography section of H-82-01 and is described in the report itself.

Design criteria and system decisions should be derived from these primary sources, for the intention of this Executive Summary is to give only an overview of historical and ongoing work in robotics and teleoperation and not to supplant the technical reports as a source of data.

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EXECUTIVE SUMMARY

The conscious combining of human and machine capabilities into an integrated engineering system is a most complex and highly interactive interdisciplinary undertaking. Remote machine operations under human control further stretch our skills and knowledge of human/machine interaction. Such human controlled remote systems are referred to as teleoperators, and this Executive Summary provides an overview of findings from the MSFC Teleoperator Technology Development Program which has sought to identify the human factors requirements for remotely manned systems. The data were developed in three principal teleoperator laboratories at MSFC, and a brief description of the visual, manipulator and mobility laboratories has been included.

The summary has been divided into three major sections: Remote System Components, Human Operator Considerations, and Teleoperator System Simulation and Concept Verification.

1.0 REMOTE SYSTEM COMPONENTS

Teleoperators are meant to extend and enhance the human's capability to perform specific tasks. They are machine systems under the control of a human operator who manages the system from a remote site.

The teleoperator system can be broken down into significant component parts, these being:

- o The operator's workstation, providing control and display information for the human so that remote tasks can be carried out at the worksite through the teleoperator.
- o The communication system, providing two-way transmission of information between the operator's workstation and the remote worksite, and for storage, analysis, transformation and retrieval of that information.
- o The remote mechanical effector, providing capabilities for sensing, manipulation and mobility at the remote site.

At MSFC, these teleoperator components have been the subject of human factors and systems research since 1971. The design guidelines derived from these evaluations follow.

1.1 Sensors and Displays

In order for the human operator to fully understand and appreciate the remote site, it is necessary for the remote system to have on-board sensory instrumentation which can relay data to the operator. For local control, it is also desirable for the teleoperator to have a "sense" of itself. Forces,

torques, pressure, speed, temperature, vision and acoustic information might be desirable for specific applications. The remote system can be designed to sense information beyond the range of the human and can transform this information for human interpretation. The displays must be compatible with operator limitations and mission requirements. Pertinent findings from the Teleoperator Technology Development Program concerning sensors and displays are as follows:

1.1.1 Laboratory Description

The Visual System Evaluation Laboratory contains all test apparatus required for evaluation of visual systems proposed for use on the teleoperator vehicle. Historically, the potential video camera/monitor systems have been installed, tested, and modified in the visual lab prior to installation and further testing in the mobility or manipulator laboratories. Basic research has also been conducted to specify detailed design requirements for the teleoperator visual system.

The laboratory equipment provides for the manipulation of any of the following parameters and shows those levels studied.

- o Transmission: black and white and color (one gun)
- o Camera/monitor configurations: 1 camera, 1 display; 2 cameras, 2 displays; 2 cameras, 1 display; and special effects generation
- o Depth of view: monoscopic, stereoscopic
- o Monitor sizes: 19.7 cm (7.75 in) diagonal, and 30.5 cm (12 in.) diagonal (standard)
- o Field-of-view of camera: 8° to 35° horizontal
- o Frame rate of display: 15 frames/sec.; 30 frames/sec.
- o Signal format: analog; digital, 4 bit
- o Signal to noise ratio: 32 dB, 21 dB, or 15 dB
- o Viewing aids: electronically generated reticles and cursors; overlaid reticles; ranging radar
- o Target motion: Fore-aft, variable translation rates; rotation, variable rates
- o Variable target parameters: shape, size, brightness, 2- or 3-dimensional
- o Variable target/background contrasts
- o Variable target/camera geometries
- o Variable scene lighting, special lighting sources.

Each of the several parameters can be combined to permit the study of system component interactions.

1.1.2 Visual System Results

- o The visual angle required for shape recognition was found to be influenced by type or shape, highly angular shapes being recognized at smaller visual angles.
- o Signal-to-noise ratios below 15 dB significantly degrade performance, while those above 21 dB do not exert such a negative influence.



- o Detection of a gap between two targets requires an average of 4.15 arc minutes for detection.
- o Generally, brightness discrimination between two targets is enhanced for contrast values of .25 or greater.
- o Size discrimination between two targets is also strongly affected by target-background contrast, and contrast ratios of .6 should be employed for size discriminations.
- o Recognition of shapes and patterns is strongly influenced by contrast, transmission format and signal-to-noise ratio, with high contrast, analog signals, and adequate S/N separation yielding the best recognition.
- o Judgments concerning fore-aft target separation are strongly influenced by camera configuration and camera type. Orthogonal monoptic camera pairs yield good results, while split field stereoscopic systems yield less accurate separation judgments.
- o Judgment of deviation from the horizontal or vertical plane is difficult to make for offsets of less than 3°, and this appears to be a threshold value for detection of angular deviation.
- o The dramatic interaction of camera line of sight, target alignment/offset and direction of target illumination was demonstrated when subjects failed to detect target misalignment of 10° when a solid target was inclined within 30° of the illumination source. The direction of misalignment could not be accurately judged for offsets of up to 35° when only the face of the target was illuminated.
- o The mode of transmission effects on visual performance. Digital transmission degrades visual acuity, as it does brightness discrimination where contrasts of .5 produced error rates of 10%. Size discrimination suffers a threefold increase in error for digital transmission relative to that of a direct 4.5 MHz mode. Narrow bandpass filtering of the transmission degrades visual acuity to a lesser extent.
- o Color discrimination should be limited to 10-14 colors for maximum discriminability. The Munsell notations for these colors are:

No.	Hue	Value/Chroma	No.	Hue	Value/Chroma
i	2.5 R	4/14	viii	7.5 G	5/10
ii	8.75 R	MAX	ix	7.5 G	4/10
iii	6.25 YR	MAX	x	7.5 BG	4/8
iv	8.75 YR	MAX	xi	3.75 PB	4/12
v	2.5 Y	8/16	xii	10.0 P	5/12
vi	2.5 GY	7/12	xiii	10.0 P	4/12
vii	7.5 GY	6/12	xiv	5.0 RP	3/10.

- o Recognition of alpha-numeric characters is influenced by character density, character contrast, viewing distance, and monitor size. Analog transmission of 4.5 MHz and 32 dB S/N will yield .99 probability of character recognition. When the character height subtends a visual angle of 30 arc min, the character width is 23 arc min and the stroke width is 5.5 arc min (futura demibold).
- o The probability of detecting target motion is increased as the absolute rate of change of the target diameter increases. Positive and negative rate changes can be detected at the 90% level at rates of .025 in/sec change in target diameter using reticle cue. For conditions without reticle cues, rates of .04 in/sec are required.
- o The range estimation of targets is dependent upon target size, brightness, contrast and comparative aids such as reticles. Movable reticles tend to improve range estimation compared to fixed reticles over a wide variety of conditions.
- o Advanced stereoscopic TV systems, such as the Fresnel display, provide enhanced depth perception, especially when combined with an electrically generated depth cursor. However, the restrictions on lateral head movement imposed by Fresnel displays must be considered in control and display design.
- o Gap resolution performance depends on signal-to-noise ratio and transmission mode. The visual angle required for detection with .90 probability ranges from five arc minutes for a 32 dB signal-to-noise ratio, regardless of transmission mode, to nearly 20 arc minutes for a digital transmission system with signal-to-noise ratio of 15 dB. The corresponding mean visual angles are 3.7 and 9.1 arc minutes.
- o Brightness discrimination performance depends on transmission mode. With direct transmission, a contrast ratio of .20 produces near certain discrimination. With digital transmission, however, ratios as high as .25 to .50 yield error rates of 5% to 10%. The time required to judge brightness differences decreases to a minimum of about one second with contrast ratios above .25.
- o Recognition of familiar geometric shapes requires a mean visual angle of 25 to 40 arc minutes depending on the shape and transmission conditions. This represents an angle twice as large for TV viewing as for direct viewing--the accepted subtense for direct form recognition being 12 to 20 arc minutes.
- o Size discrimination performance depends on target-background contrast. With contrast ratios of .625, the linear dimension size discrimination threshold is on the order of $\pm .10$. Reduced contrast of .125, however, raises the threshold value to $\pm .30$.

- o Estimation of single target size depends on target-background contrast and true target size. Percent absolute size estimation error ranges from 15% to 40% depending on the values of these variables.
- o Estimation of target separation in the fore-aft direction depends on camera mode and true separation. Mean absolute estimation error expressed as a percentage of true separation varies from 10% to 30% depending on true size for an orthogonal monoptic viewing system to as much as 50% to 70% for a system using single camera stereoptic viewing in the target plane.

1.2 Manipulation

General and special purpose manipulators can perform a wide range of effective tasks at the remote site, particularly with specialized end effectors such as tool attachments. The manipulators can resemble human arms or they can be made longer, thinner, stronger, and more dexterous than human arms, or designed to almost any specification required by the task. Manipulator systems which have been evaluated under the Teleoperator Technology Development Program are listed in Tables 1-1, 1-2 and 1-3, and the results from the investigations are summarized below.

Table 1-1: Manipulator Arm Subsystems

Manipulative Arm	No. of Arms	Configuration
Rancho Los Amigos	Two	Anthropomorphic
Ames Hardsuit	One	Anthropomorphic
Extendible Stiff Arm Manipulator (ESAM)	One	Non-Anthropomorphic
Advanced Dexterous Anthropomorphic Manipulator System (ADAMS)	Two	Anthropomorphic
Protoflight Manipulator Assembly (PFMA)	One	Non-Anthropomorphic

Each of these manipulator arms could be terminated with a working end effector for performance of teleoperated dexterous tasks.

Table 1-2: End Effector Subsystems

Effector Name	Description
Dorrance Effector	Classic general purpose curved prosthetic hook with grasping accomplished by closing opposed jaws
Protoflight End Effector	An opposed jaw type, general purpose effector with adaptive grooves for clamping tools
Terminal Kit Adaptor (TKA)	A collection of special purpose tool heads which can be mounted in a terminal receptacle fitted to a manipulator arm. Tool heads include wire cutter/strippers, hexagonal head wrenches, pliers, socket wrenches, and padded opposing jaws
RMS End Effector Capture Device	A special purpose can-type with an internal snare for capturing docking probes
MSFC 3 Finger Grappler	A special purpose grapppler end effector for securing a trailer hitch ball probe
Opposed Jaw	General purpose end effectors, of which several types were studied

There are several other end effectors which are available for study, notably the tactile/force sensing end effector which is equipped with proportional touch sensors in the jaw pads, the mechanically actuated trigger hand (MATH) for the grasping and triggered operations of standard power tools, and the attached optical array proximity sensor which permits sensing the near environment of the end effector prior to actual physical contact with the task elements.

Table 1-3: Controller Subsystems

Controller Name	Degrees of Freedom	Control Type	Characteristics
MIT Isometric (SD-2)	6	Computer Resolved	No force feedback; no position feedback; suffers cross coupling effect
Lever Analog MSFC	6 + End Effector Open/Close	Electro-mechanical drive link	Offers position & rate control
Analog Joystick	6 + End Effector Open/Close + Telescoping Extension	Electro-mechanical link resolved rate	Partial replica control of ESAM
Terminal Pointer	5 + End Effector Open/Close	Computer resolved proportional rate	Provides spatial correspondence between operator's hand & end effector; controls tip position
MSI Isometric 544	6	Computer resolved proportional rate	Single hand control of 6 DOF
MSI Isometric	6 + Open/Close Jaw	Computer resolved position or rate control	Single hand control of 6 DOF
AMES Exoskeletal	6 + Open/Close End Effector	Electro-mechanical linkage	Exoskeletal full arm and hand controller
ADAMS Master/Slave	6	Electro-mechanical linkage	Exoskeletal replica controller

1.2.1 Laboratory Description

The Manipulator System Evaluation Laboratory provides the laboratory space and testing hardware necessary to collect quantitative data on manipulator systems. The primary elements of the laboratory are:

- o A manipulator arm with associated hand controller(s), computer electronic subsystems, and visual systems
- o A task board to simulate typical servicing or assembly tasks
- o A remote operator's station that provides all controls and displays necessary to operate the manipulator and visual systems
- o An experimenter's station that provides the controls necessary to conduct the tests and the displays necessary to record performance data.

A manipulator room contains the manipulator arms under evaluation along with support equipment (lights, cameras, power supplies and task boards). The experimenter is stationed near the manipulator so direct visual observations of any arm may be made. A task board is positioned in the room near the appropriate arm. Task scene feedback is accomplished through the stereoscopic or monoscopic video system.

The operator's control room contains the operator's station, from which communications between the experimenter and operator are maintained via headsets. This isolation minimizes auditory feedback from the manipulator operations. At the station, the manipulator hand controller is placed in front of the operator, below the video monitors. Ambient lighting is provided by a diffused overhead fluorescent lighting.

The third room, located between the control room and the manipulator room, houses a SEL 840A computer. It is through this computer that the selected controller outputs are transformed into manipulator commands.

1.2.2 Manipulator System Results

- o Manipulator arms must be appropriately matched to the hand controller by degrees-of-freedom, operating correspondence and task requirements, and freedom from cross coupling in order to maximize system performance.
- o Movements of the manipulator tip require more time for accurate terminal positioning and more time for large movements based on the equation:

$$\text{Index of Difficulty} = \log_2 \frac{2(\text{amplitude of movement})}{\text{terminal target tolerance.}}$$

- o Integrated hand controllers of up to 6 DOF have better demonstrated performance when freedom from spurious movement is reduced by adding friction to the controller joints or by reducing the gain in the controller. This provides some reduction in cross coupling effects, and reduced task time as well as increased positioning accuracy.
- o The direction of movement has been shown to have a significant effect on task performance time, but is largely dependent upon the type of controller and manipulator arm being employed.
- o The time to perform insertion and removal tasks is slightly increased for conditions where the task is offset in yaw with respect to the camera/manipulator line-of-sight.
- o The time to insert and remove pegs decreases as the pegs increase in diameter. This conforms to Fitt's law and the Index of Difficulty Equation.
- o Isometric controllers appear to offer some control advantages over isotonic controllers provided that the effects of cross coupling have been minimized in integrated controllers.
- o Work place layout and task arrangement should be carefully organized for tasks involving manipulator use. This is based on the findings which show increased time to perform offset tasks and tasks located along particular vectors.
- o The application of split controllers--those with attitude and translation incorporated in separate controls--should be limited to systems which apply to only one manipulator unit. The application of two manipulator arms will necessitate an integrated controller for each.
- o The evaluations of manipulator systems--controllers, arms, end effectors, feedback devices and control programs--should be accomplished through a standardized and hierarchical evaluation program which begins with simple, minimal degree-of-freedom tasks and proceeds through complex and mission-specific tasks. This provides for the early elimination of systems which fail to meet operational criteria of a manipulative task.

1.3 Mobility

Transportation to or about the remote site is provided by several classes of mobility systems: gas jets for space travel, propulsive screws for water environments, tracks and wheels for terrestrial environments, propellers and wings for airborne vehicles. Other mobility system examples are surface effects systems, rail guides, air bearings, crawlers, and similarly special systems. The goal is to provide maneuverability at the remote site for task performance at numerous locations.



The mobility system employed in current testing is remotely controlled in five degrees-of-freedom through a translation and attitude two-joystick hand controller system. The mobility unit propulsion system uses compressed air operated through four groups of four thrusters each that provide pure moment and axial thrust.

1.3.1 Laboratory Description

The Mobility Systems Evaluation Laboratory at MSFC has been used to evaluate command and control systems and docking hardware since 1974. The free floating mobility unit (MU) and associated control hardware were designed to simulate a small, unmanned, remotely controlled space vehicle operating in a near proximity rendezvous and docking situation. This capability has been extremely useful for the evaluation of teleoperator equipment such as crew hand controllers, camera positions, video displays, and docking probes. Crew procedures and equipment operating characteristics have also been evaluated.

The mobility laboratory₂ is located in the high bay area of Building 4705 at MSFC and contains a 111 m^2 (1200 ft^2) flat floor, a free floating MU, and an operator control room.

The flat floor is a poured, black epoxy surface (type Moran 109-B-71). It is basically circular with a diameter of 11.6 m (38 ft) and is enclosed in a $12.2 \times 12.2 \times 6.1 \text{ m}$ ($40 \times 40 \times 20 \text{ ft}$) test area of black, light absorbing curtains. The epoxy, poured to a depth of 3.3 cm (1.3 in), forms a precision surface with less than 0.02 cm variation measured over 125 separate locations. Air conditioning is provided to maintain a constant temperature and to minimize the accumulation of dust on the test surface floor.

The test area is illuminated by four banks of two-1250 watt quartz iodide lamps suspended from the ceiling in the enclosure corners and angled to converge the greatest illumination near the center of the floor. Additionally, a Spectrolab Night Sun, SX/16, search light is installed in the test facility to serve as a source of simulated solar illumination. The light unit is a xenon plasma arc lamp that generates a peak beam of 20 million candle-power from an input of 28 Vdc at 65 amps. The lamp is mounted 3.2 m (10.5 ft) above the laboratory's air bearing flat floor on a remotely controlled pan and tilt unit for target tracking.

Adjacent to the test area is the operator's test console which is enclosed in a 9.0 m^2 (95 ft^2) sound-insulated room. The test console contains much of the same type of equipment that may be used in the Shuttle aft cabin control station for the control of teleoperated activities.

The air bearing system consists of three 30.5 cm (12 in) circular pads, pressure regulated at $2.4 \times 10^5 \text{ N/m}^2$ (35 psi) to float the vehicle with a .05 mm (.002 in) clearance. The total volume₃ of compressed air stored in the lower bay of the vehicle is $.073 \text{ m}^3$ (2.604 ft^3) at a pressure of $10.3 \times 10^6 \text{ N/m}^2$ (1500 psi).

The lower bay houses the compressed air supply, contains the air pads, and supports the upper bay. It also serves as a mounting support for the air bearing pedestal upon which the MU is free to roll and pitch about a center point. This lower bay is 48.3 cm high and 116.8 cm in diameter (19x46 in) and is painted a non-reflective flat black to minimize the operator's visual cues.

The propulsion system of the MU, as mentioned earlier, serves the dual purpose of vehicle translation and attitude control. Each group of four thrusters is clustered about the longitudinal axis of the vehicle (one group at each corner). Each thruster is controlled by a solenoid valve at the thrust chamber injector and was measured at approximately 4.45 N (1 lb) thrust for 4.12×10^4 N/m² (60 psi) plenum pressure and a 100 msec. pulse duration. Total volume of compressed air for the upper bay of the vehicle is 0.074 m³ (2.6 ft³) at a rated pressure of 10.3×10^5 N/m² (1500 psi).

The unfueled mass of the MU is 752.4 kg (1262 lb) of which 419 kg (923 lb) is the top bay. Fueling the MU adds 18.46 kg (40.7 lb) to the total mass. However, half of this is used for the air bearing pads, leaving 9.2 kg for use by the propulsion system.

1.3.2 Mobility System Results

- o Rendezvous and docking tasks with large mass targets—those of a mass greater than the teleoperator—required 135 seconds and 150 Δ psi of fuel to accomplish a hard dock between the two vehicles. Docking with low mass targets required 227 seconds and 214 Δ psi of fuel due to the ability of the teleoperator to "push" the low mass target around.
- o The differences in constant thrust and trained pulse (5.5 pulses/sec) were significant for fuel expended during a docking task (228 Δ psi for constant thrust and 138 Δ psi for trained pulse), and the trained pulse also demonstrated a slight advantage in time to dock—193 sec. vs. 169 sec.
- o This difference was demonstrated in standoff approach and docking tasks with the trained pulse mode yielding mean times for approach and dock of 210 sec. versus 302 sec. for constant thrust. While not a statistically significant variation, it does tend to support the results of other thrust mode studies. The same trend was apparent in the use of fuel with the pulsed thrust mode requiring 30% less fuel than the constant thrust mode.
- o In controlling a two vehicle docking task, the time and fuel consumption differences between a one-hand integrated controller and two-handed attitude and translation controllers were slight, and the apparent advantage mixed:

Single hand controller - 193 sec. and 177 Δ psi
Dual hand controller - 169 sec. and 188 Δ psi.

- o When controlling a docking probe on a low mass vehicle, some more apparent advantages to the single hand controller are demonstrated. The probe was an extendible/retractable lock type probe which fitted into a ring capture device rather than a conical drogue. The time and fuel expended to dock for a single and dual hand controller system were:

Single hand controller - 80.8 sec. and 58.75 Δ psi
Dual hand controller - 112.6 sec. and 60.0 Δ psi.

- o Current mobility studies have not demonstrated a significant difference between center mounted (bore sighted) camera systems, and off center (top mounted) cameras aimed at a docking target. The mean time to close from 6 m and dock using a bore sighted camera was 98.75 sec, while the mean time for an off-center camera was 94.3 sec. Mean fuel expenditure for boresighted trials was 81.5 Δ psi, and 85.0 Δ psi for off center camera trials.
- o During docking tasks, the operator should be provided with scene lighting for illuminating shadowed docking probes and should also have manual control of sensor iris and target sensitivity so that image blooming of highly illuminated surfaces can be compensated for at the display. Automated sensors have tended to obscure targets of interest which may be in highly illuminated or deeply shadowed areas due to their "averaging" the task scene lighting conditions.
- o In comparison of trained pulse, constant thrust and a single pulse mode over target offset conditions of $\pm 45^\circ$ misalignment, the trained pulse mode continues to exhibit an advantage in performance time:

For trained pulse - 166.2 sec
For constant thrust - 181.8 sec
For single pulse - 451.8 sec

while the single pulse mode demonstrates the worst performance for docking tasks.

2.0 HUMAN OPERATOR CONSIDERATIONS

The human senses play a critical role in our ability to manage our daily activities. Sight, smell, hearing, touch, taste, temperature, and balance are some of the sensations on which we rely as we move about our world. How we sense, as well as what we sense, are significant considerations in the design of complex human controlled remote systems. Understanding this enables us to take advantage of the inherent capabilities of the human perceptual system while augmenting it where necessary for the appropriate control of tele-operated activities. This section deals with the apprehension, processing and behavioral consequences of environmental energy impinging on the human.

2.1 Vision

Seeing is our sensory evaluation of that portion of the electromagnetic energy spectrum from approximately 400 nanometers to approximately 800 nanometers. Radiated or reflected energy within that range which reaches the eyes is converted and passed to the brain, giving rise to vision. Since vision is considered a critical feedback mode for controlling remote systems, a short discussion of vision is in order.

2.1.1 Psychophysics of Vision

Detection - The initial function of the sensory system is to detect the presence of energy in the environment. Detection is the magnitude of a given stimulus (relative to a zero energy level) that is necessary for an individual to determine that something has been sensed. This minimal amount of energy is the "absolute threshold," and for the eye it has been determined to be one-millionth of a ft. lambert.

There is a hierarchical relationship between detection and recognition. Recognition requires that more stimulus information be available than for simple detection. The number of bits of information that can be perfectly recognized along a single continuum is approximately 7 ± 2 , depending on the continuum addressed (a bit being defined as $\log_2 n$, where n is the number of stimulus alternatives). Also, the greater the number of stimulus dimensions, the better the recognition. Thus, many investigators have placed more emphasis on the quality or kind of information and the characteristics of the processor, and less emphasis on the quantity of information available.

Discrimination - As opposed to detection and recognition, discrimination focuses upon the question of the amount of disparity which must exist between two stimuli in order for them to be judged as being different. In a discrimination task, an observer must decide whether a signal came from one of two or more distributions along the same dimension, as compared to a detection task where a stimulus must be ascertained as coming from a signal or a noise distribution.

Visual Acuity - A fundamental physiologically-based function of the eye is its ability to resolve details or its degree of visual acuity. Visual acuity is a function of several variables, i.e., visual angle, brightness, contrast, image size and color. Acuity tasks are really forms of brightness discrimination since details to be resolved are basically defined by brightness differences in a strong relationship between visual acuity and the distribution of rods and cones on the retina. Since there are more cones in the central area, the fovea is the site of greatest acuity. The range of clear vision extends less than 10° away from the foveal center.

The visual angle, or the angle subtended at the eye by the viewed object, is usually expressed in arc minutes. The formula for this value is as follows:

$$\text{visual angle (min)} = \frac{(57.3)(60)L}{D}$$

where L = the size of the object measured perpendicular to the line of sight and D = the distance from the eye to the object. The 57.3 and 60 are constants for angles less than 600 min.

The amount of contrast in the visual field is a factor having a strong relationship to visual acuity. Contrast is the measure of luminance (measured in Lamberts) difference between a target and its background. It can be computed by this formula:

$$\text{contrast (\%)} = 100 \times \frac{L_b - L_t}{L_b}$$

where L_t = luminance of the target and L_b = luminance of the background; reflectance can also be substituted for luminance.

Assuming maximum contrast between a line and its background, at the lowest intensity of light, the eye can see a line whose width subtends a visual angle of 10 minutes. At very high intensities, the eye can see a line subtending a visual angle of less than 1 second.

2.1.2 Color Vision

Color consists of three attributes--hue, brightness and saturation. While some observers are capable of discriminating over 150 hues, the average person can accurately and reliably label only eight or nine hues. Color recognition depends on several factors, i.e., the color of the light source, the color of the reflecting surface or surfaces, and the state of the observer's visual system. Pale colors are more easily influenced by the color of the light being reflected by nearby surfaces. They are highly influenced by the level of illumination as well as the inherent reflectivity characteristics of the surface viewed.

2.1.3 Critical Flicker (Fusion) Frequency

The update, or refresh, rate on a TV monitor often causes the scene to "blink" or flicker. A visual phenomenon which is important to consider in this regard is the critical flicker (fusion) frequency (CFF). As an observer views a flickering light, it will eventually appear to be a steady, continuous light as the flicker rate is increased. Thus, the TV update rate should be fast enough to reach this frequency, ~30 Hz.

2.2 Proprioception

Kinesthetic and vestibular senses are two somatic, or bodily, senses which closely interact to maintain balance and provide information about the internal state of joints and muscles and about gravity. They jointly account for the human's ability to perceive (1) the position and orientation of the body and limbs, (2) the movement of the body and limbs, (3) the position or

attitude of vehicles with a human in the vehicle, and (4) the movement of vehicles with a human in the vehicle. These senses take on added importance in the absence of, or with reduced, visual information. There are times, however, when they provide erroneous information and may conflict with visual information.

The absolute threshold for perception of motion by the vestibular sense is between 0.1° and $0.5^\circ/\text{second}$. The delay in perception of velocity and acceleration change is greater for the vestibular sense than for the kinesthetic sense. For instance, with an angular acceleration of $10^\circ/\text{second}^2$, motion perception occurs in about 1 second; if the angular acceleration is only about $0.5^\circ/\text{second}^2$, it may take as long as 10 to 12 seconds to perceive the motion.

It is extremely important that the sensations provided by the vestibular senses not be in conflict with visual or kinesthetic sensations. Any conflicting sensations of this sort can lead to debilitating feelings of disorientation. Rotation of the body, tilting of the head when the body is rotating, rotation of the body opposite from that of a vehicle on which the person is riding, or vertical oscillation can result in profound disorientation and often motion sickness.

There are two main factors which can influence the kinesthetic and vestibular senses. While there are definite individual differences in sensitivity to kinesthetic stimuli, the most important source of variation is the result of the human's ability to learn to interpret these cues accurately. With enough practice a person can learn to position a control quite accurately without visual cues. Also, the absence or reduction of the earth's normal gravitational field results in the reduction or loss of many kinesthetic cues.

For design purposes, however, the capabilities of the kinesthetic and vestibular senses are most significant in the design of controls where they aid in the positioning of controls without visual cues. Both senses also provide some information for the attitude and change of motion of vehicles. When designing vehicles, the most important consideration is to avoid rotations or oscillations which are conflicting or disturbing or may cause motion sickness.

2.2.1 Strength, Endurance and Dexterity

Strength is the maximal force muscles can exert isometrically in a single voluntary effort, or the muscular capacity to exert force under static conditions. Muscle force is a function of several variables, some of which are:

Muscle tension - is maximum when the length of the muscle is greatest and there is no change in the length for a period of time. Muscle force decreases as the rate of shortening increases.

Mechanical advantage - occurs at the midpoint of full elbow travel. This is because optimum mechanical advantage more than compensates for the shortened muscle.

Thermal environment - When humidity is high and temperatures exceed 85°F, strength is adversely affected. Low temperature, however, has little impact except in relation to body mobility and finger dexterity.

Acceleration - Accelerations up to 5 g's do not affect strength but do affect endurance. Arm movements are effective up to about 6 g's and wrist and finger movements are effective up to about 12 g's.

Emotional condition - Strength may increase under stresses such as fear, panic and rage; but skill and accuracy are degraded.

Body and limb position - Since there is usually a reciprocal response during force applications (e.g., lifting, pushing and pulling), it is important to provide adequate support and anchoring. Limb position and direction of force application are the most important variables in determining the amount of force an individual is capable of applying. They must be considered together for each specific operational requirements.

Endurance is the ability to continue work or exert force over time. There is a nonlinear, inverse relationship between the fraction of the strength which must be exerted and the time over which it can be exerted. One hundred percent of strength can be exerted for only a few seconds; only a fraction (15%-20%) of maximal strength can be maintained for several hours without fatigue.

Designers should be constantly mindful of the fact that where the operation of equipment is highly dependent on manual dexterity or skill and practice, there is considerable opportunity for error. The equipment should therefore be designed so as not to place unreasonable demands on dexterity, precision, speed, or highly sensitive responses to a wide range of cues. It is important to understand the characteristics of the human sensorimotor servosystem and design so that lags in the human system are taken into account.

Although the average person may perform certain control manipulations more accurately than others, considerable dexterity may be developed with practice. In general, performance levels can be expected as follows:

1. Rotational manipulation is more accurate than either sliding manipulation or movement of thumb or finger wheels. Performance with thumb or finger wheels, in turn, is more accurate than with sliding manipulation.
2. Rotation in a horizontal plane is more accurate than rotation in the vertical plane. Horizontal accuracy depends on the ability of the operator to rest his or her hand on the adjacent surface.
3. A pushbutton is located and pressed more accurately when positioned in a horizontal plane.

4. A pencil-sized joystick is manipulated more precisely than one requiring a full fist grip. The accuracy is also increased significantly if the operator's arm can be rested on a nearby horizontal surface.

2.3 Psychomotor Learning and Feedback

Skills which involve motor activity are generally characterized by three features: the organization of sequences of motor movements and/or symbolic information; a purpose, goal or desired target state toward which the sequence is directed; and, corrective reactions based on feedback from the consequences of previous actions.

The operation of teleoperator systems may be considered to be a continuous adjustment control response. Control effectiveness in this case depends on several factors:

- o The ability of the operator to anticipate and predict what is going to happen when input is provided to the system.
- o Feedback on a timely basis about what is happening as control inputs are made.
- o The amount of differentiation, integration and/or algebraic addition the control and display task requires of the operator. These should be minimized.
- o How well the specific control and display devices provide compatible relationships between the operator's sensory, perceptual and motor and physical abilities and limitations.

It is important to be cognizant of the following factors which degrade control effectiveness:

- o Long delays between inputs and feedback, e.g., perceived changes in incoming information, results of operator inputs on system, or direct feedback from controller manipulation.
- o Too much noise in the system, e.g., extraneous signals, dynamic disturbances, or mechanical artifacts such as "dead space," "stiction," and force irregularities.
- o Incompatibilities between control and display direction and rate of motion.
- o Controller force requirements are too high or too low.
- o Incompatibility of the position, direction, and range of movement of the controller with operator's position and physical capabilities.

- o A requirement that an inappropriate body element be used, e.g., the hand versus the foot, the left hand versus the right hand, or the whole limb versus the hand and fingers.

2.4 Audition

The absolute threshold of hearing is a value which represents for audition the same concept as for other sensory modalities. It is the minimum sound-pressure level of a specified sound that is required to elicit the sensation of hearing in a specified fraction of trials (about 50%). The value of the absolute threshold depends on the type of sound (its frequency, duration, repetition rate, method of presentation) as well as characteristics of the listener. The ear is most sensitive to sounds with frequencies between 2000 Hz and 5000 Hz and about 100 times less sensitive to sound at 100 Hz than to sound at 3000 Hz.

There are several conditions under which an auditory signal may be preferred to other types of signals:

- o As a warning signal. A visual warning must be seen in order to be effective. Alternately, hearing is omnidirectional and cannot be involuntarily turned off. It is, therefore, the best modality to which attention to imminent or potential danger should be called.
- o In situations where one visual display has nearly complete attention of the operator or when too many visual displays are already presented.
- o Where information must be presented independently of head orientation, as in cases where duties require body movement or head turning.
- o Under conditions of anoxia or high positive g forces. Audition is more resistant to anoxia than vision.
- o When signals must be distinguished from noise.
- o When the information provided is short, simple and transitory and requires immediate or time-based responses.
- o As a redundant or supplementary transmission of critical information.
- o Where custom or usage has created an anticipation of an audio display.

The effective design of an auditory display must give proper consideration to the sound environment within which it will operate. An auditory signal can otherwise be easily obscured by extraneous noise or sounds in the environment. The frequency range should be between 500 Hz and 3000 Hz. Whatever frequency band is selected should differ from the most intense background

frequencies. Also, the number of signals to be discriminated should not exceed four. Once a particular auditory code has been established for a given operating situation, the same signal should not be designated for some other display.

2.5 Transformation of Information to Perceptible Formats

The human sensing system is in many ways extremely accurate, versatile and sensitive. There are, however, many circumstances in which information critical to the performance of some activity must be presented indirectly by the use of some type of display.

1. When stimuli from the environment are such that they are beyond human sensory capabilities entirely. These stimuli (e.g., electromagnetic radiation beyond the spectrum to which humans are sensitive and ultrasonic vibrations) must then be sensed by specialized sensing devices and converted to an appropriately coded form for human perception.
2. When stimuli are of the type that humans can generally sense, but are not able to sense adequately, as is the case in knowing the shape of large land masses through maps.

Although a design meets or exceeds a sensory threshold for detection or differential sensitivity, it still may not be adequate for sensing under adverse operating conditions. A designer may assume that once having attained threshold levels, any further increase may be a luxury. While this assumption may be valid under ideal conditions, it is not likely to be the case in an operational environment where stress or boredom is added. For this reason, human factors specialists test designs under conditions as nearly like the operational environment and workload as possible prior to acceptance of the final design.

2.5.1 Control/Display Design and Format

Effective and efficient man-machine systems depend upon equipment design features which make full use of human performance capabilities and also recognize human limitations. From a system's point of view, human capabilities and limitations are seen in terms of receiving, coding and transmitting information which interface with machine components of the system. Although both the human and machine components are subject to factors in the physical environment, humans are particularly affected by conditions which may overstress or understimulate them. Environmental factors, physiological factors and task demands interact to determine the total load on the operator.

The criteria for design are dependent to a large extent on mission requirements and other factors external to the system. However, body of knowledge has been developed which addresses specific design in the determination and application of human factors engineering guidelines to a teleoperator system:



- o MIL-STD-1472C, Human engineering design criteria for military systems, equipment and facilities. 1981.
- o Woodson, W.E. Human factors design handbook. McGraw-Hill, Inc., New York, 1981.
- o VanCott, H.P. and Kinkade, R.G. (Eds.). Human engineering guide to equipment design (Rev. ed.). American Institutes for Research, Washington, D.C., 1972.
- o McCormick, E.J. Human factors engineering. McGraw-Hill Book Company, New York, 1970.
- o Chapanis, A. Man-machine engineering. Wadsworth Publishing Co., Inc., California, 1965.
- o Woodson, W.E. and Conover, D.W. Human engineering guide for equipment designers. University of California Press, Berkeley, California.

3.0 TELEOPERATOR SYSTEM SIMULATION AND CONCEPT VERIFICATION

Through simulation, the duplication of known or expected mission variables into a training or research program has provided a low cost, low risk means of investigating overall system performance. Simulation is widely used in aerospace programs to train pilots and astronauts in flight procedures and to verify the interaction of the human operator with the hardware components in the accomplishment of the proposed mission objectives.

In support of the design, development, integration, and validation of space teleoperator systems, simulation capabilities can be classified in terms of their basic purpose, such as:

- o Research on human capabilities, requirements and roles
- o Teleoperator technology development
- o Teleoperator system integration
- o Teleoperator system validation.

3.1 Neutral Buoyancy Simulator Facility

MSFC'S Neutral Buoyancy Simulator (NBS) facility is a 1.4 million gallon water tank in which system mockups can be made neutrally buoyant, simulating low gravity conditions. The simulator provides an environment where six degrees-of-freedom motion can be achieved for free flying mockups, EVA operations by suited test subjects, remote manipulator system operations, and similar large scale simulations. The 75-ft diameter and 40-ft. depth of the tank provides ample room for simulations of Shuttle payload bay operations, including the remote control of payloads. In the past, free flying vehicles have "flown" in the NBS powered by underwater motors representing thruster modules.

Given appropriate calculations to overcome or describe the water drag characteristics and careful selection and buoyancy of the test article or mockup, the NBS is an especially good facility for extended simulations and multiple replications of teleoperated tasks. It provides a low cost, relatively uncomplicated environment for verifying teleoperator system concepts and for examining the human operator's capabilities in conducting 6 DOF remote tasks.

3.2 Motion Base Simulator

The 6 DOF motion base simulator is a hydraulically actuated motion table located at the MSFC Computation Laboratory. Originally designed as a flight simulator to provide acceleration cues to flight crew members who occupied the attached flight deck, the motion table has undergone modifications to accommodate control of teleoperated activities. During the Skylab reboost effort, the Teleoperator Retrieval System (TRS) capture device was mounted on the motion table and the Multiple Docking Adapter (MDA) was attached to a ceiling frame over the motion table. A remotely located operator controlled final approach and docking via television displays and two hand controllers. The performance characteristics of the motion system are shown in Table 3-1 for each of the degrees of freedom.

Table 3-1: Motion Table Performance Characteristics

	POSITION	RATE
Pitch	+30°, -20°	±15°/sec.
Roll	+22°, -22°	±15°/sec.
Yaw	+32°, -32°	±15°/sec
Vertical	39 in. up, 30 in. down	±24 in./sec.
Lateral	±48 in.	±24 in./sec.
Longitudinal	±48 in.	±24 in./sec.

The range of motion is not as large as that available in the NBS but the control and accuracy of motion are much greater; consequently, for terminal tasks such as final docking, remote structure mating or grappling, it is preferable in terms of data reliability to use the motion base simulator.

3.3 Target Motion Simulator

The Target Motion Simulator (TMS) located in the Computational Laboratory provides the capability to simulate distant approaches with considerable rate and position accuracy. It is most simply described as a target gimbal (roll, yaw, pitch) and a camera gimbal (roll, yaw, pitch) that travel along two translation rails. The simulator generally operates at 48:1 scale and the operating characteristics for this are shown in Table 3-2.

Table 3-2: Target Motion Simulator (Gimbal/Track)
Performance Characteristics

MOTION SERVO	POSITION TRAVEL	POSITION ACCURACY	MAXIMUM VELOCITY
Target Roll	$\pm 180^\circ$	$\pm \frac{1}{2}^\circ$	$\pm 50^\circ/\text{sec.}$
Target Yaw	$\pm 90^\circ$	$\pm \frac{1}{2}^\circ$	$\pm 10^\circ/\text{sec.}$
Target Pitch	$\pm 90^\circ$	$\pm \frac{1}{2}^\circ$	$\pm 10^\circ/\text{sec.}$
Camera Roll	$\pm 180^\circ$	$\pm 1^\circ$	$\pm 75^\circ/\text{sec.}$
Camera Yaw	$\pm 90^\circ$	$\pm \frac{1}{4}^\circ$	$\pm 5^\circ/\text{sec.}$
Camera Pitch	$\pm 90^\circ$	$\pm \frac{1}{2}^\circ$	$\pm 5^\circ/\text{sec.}$
Linear Motion (48:1 scale)	500 ft.	± 8 in.	± 100 ft./sec.

The operator "flies" the camera toward the target and the computer resolves the command inputs into target and camera translation and attitude changes. The singular disadvantage with this simulator is that actual docking cannot be accomplished at the conclusion of a long approach task. For this, the simulation control must be switched to the motion base simulator for the final closure and docking. The controlling software can accomplish this scene transition without total disruption of the simulation, but there is a noticeable shift in the scene and the definition of the viewed target as the scene shifts from a 48:1 scale model to a 1:1 mockup.

3.4 Proposed Teleoperation and Robotics Evaluation Facility

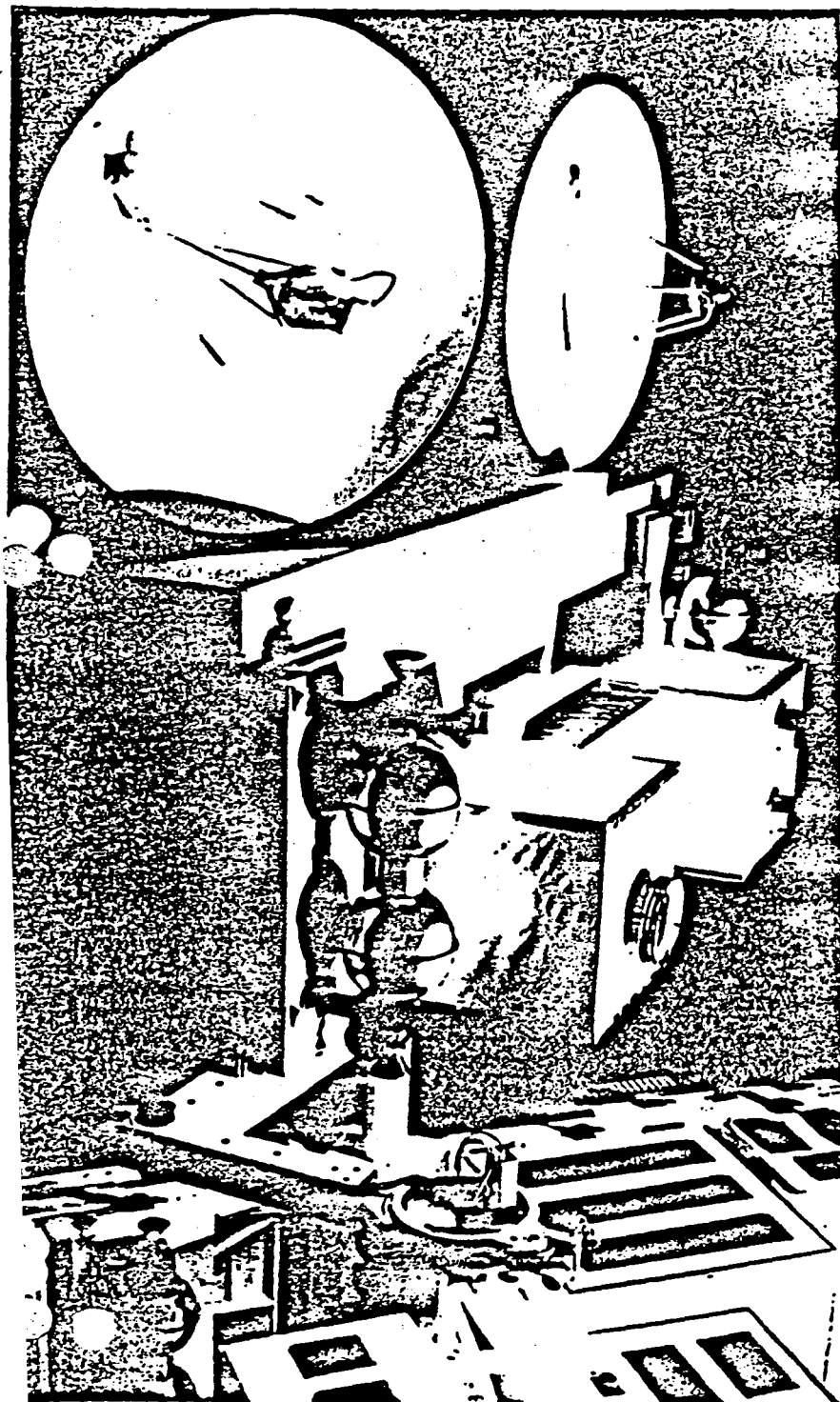
During 1980-1981, architectural and engineering drawings were developed for an extensive simulation facility in MSFC's Building 4619. The facility will build on developed technologies from the several separate simulation facilities such as air bearing floors, variable drive simulators, precision target, gimbals, 6 DOF mobility units, manipulator and visual system evaluation facilities, and computational facilities. The advantages of the proposed integrated facility will be to perform large scale simulations without having to move from one simulator system to another or contend with water drag on the test mockups as occurs in the NBS.

As currently envisioned, the Teleoperation and Robotics Evaluation Facility will have a 4000 sq. ft. air bearing epoxy floor capable of supporting the operations of several air borne mobility units. Additionally, a standoff area at the end of the epoxy floor will support large stationary systems such as the Automated Orbital Servicer or the Protoflight Manipulator Assembly System which can be used in concert with mobility units. A visual system evaluation area and visual system shop are planned for the facility as is a manipulator and hand controller evaluation area. Computational support will be available from the facility's analog and digital computers as well as microprocessors which can be integrated into the mobility and target units.



The facility will offer a wide variety of general purpose mockups such as the Multimission Modular Spacecraft and the Teleoperator Maneuvering System, with the capability to quickly change out mockups for special evaluations. The mobility units will permit active manipulation or grappling while still maintaining the commanded vehicle attitude, and this will also permit the operation of remote camera booms.

Advanced planning calls for the installation of a 6 DOF overhead target motion system which will permit simulations of flyarounds and other independent 6 DOF tasks. This will provide enormous simulation capability with a high degree of data reliability and validity.



HUMAN OPERATOR PERFORMANCE OF REMOTELY CONTROLLED TASKS

A Summary of
Teleoperator Research

Conducted at
The George C. Marshall Space Flight Center
1971 - 1981

MARCH 1982

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